MAGNETIC ATTITUDE CONTROL FOR NANO-SATELLITES

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A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical - Mechatronics and Automatic Control)

Faculty of Electrical Engineering

Universiti Teknologi Malaysia

JANUARI 2014

To my parents,

my beloved wife Norhaliana

and my wonderful daughters Sarah and Sofia

for being there for me throughout the

entire master program.

ACKNOWLEDGEMENT

Praise to Allah SWT the most merciful and the most compassionate for the guidance and knowledge bestowed upon me, for without it I would not have been able to come this far. Peace is upon him, Muhammad the messenger of Allah.

I wish to express my sincere appreciation to my supervisor, Dr. Mohamad Noh bin Ahmad @ Mohd Sanif for his encouragements, guidance and motivations throughout the year.

My sincere appreciation also extends to all my colleagues at Pusat Angkasa Negara, for the understandings and support.

Finally, I would like to thank my family for their constant encouragement and passionate love during my study.

ABSTRACT

The active magnetic attitude control technique is a recognized attitude control option for small satellites operated in Low Earth Orbit (LEO). The purpose of this thesis is to control a nano-satellite that is operated in LEO so that it always pointing toward the Earth. Two options of control algorithms have been considered for a gravity-gradient satellite. The first control is a passive type, structured for the gravity-gradient satellite (Satellite A). It relies totally on the orbited body's mass distribution and gravitational field. The second control is an active type, structured for the gravity-gradient satellite employing three magnetic torquers onboard (Satellite B). The control is accomplished using a set of magnetic torquers that can generate a mechanical torque thus producing control actions when the torquers interact with the geomagnetic field. The algorithm used in Satellite B is configured for controlling roll, pitch and yaw attitudes using a proportional-derivative (PD) controller. Both control algorithms are simulated using the MATLAB®/ SIMULINK® software. The control algorithms were tested using a simplified geomagnetic model for a reference space mission. Their attitude performances were compared and it is found that both controls fulfil the mission requirements. However, the system in satellite B gives a better attitude performance. Specifically, the roll axis oscillates between -2.4° and 3.2° while the pitch axis oscillates between -2.4° and 2.0°. Finally, the yaw axis swing is much controllable with an oscillation between -1.7° and 0.4°. This work provides us an insight when designing a real magnetic attitude control subsystem for nano-satellites.

ABSTRAK

Teknik aktif magnetik kawalan atitud ialah salah satu teknik pilihan yang diiktiraf untuk satelit kecil yang beroperasi di Low Earth Orbit (LEO) . Tujuan kajian ini dijalankan adalah untuk mengawal nano-satelit yang dikendalikan di LEO supaya ia sentiasa mengadap ke arah Bumi. Dua pilihan algoritma kawalan telah dipertimbangkan untuk jenis satelit berstrukturkan kecerunan graviti. Kawalan yang pertama adalah jenis pasif, berstrukturkan satelit kecerunan graviti (Satelit A). Ia bergantung sepenuhnya pada pengagihan jisim satelit yang mengorbit dan medan graviti. Kawalan yang kedua adalah jenis aktif yang berstrukturkan satelit kecerunan graviti dengan menggunakan tiga rod pengilas magnetik (Satelit B). Kawalan ini dilaksanakan dengan menggunakan satu set pengilas magnetik yang boleh menjana kilasan mekanikal dengan menghasilkan tindakan kawalan apabila pengilas berinteraksi dengan medan magnet bumi. Algoritma yang digunakan dalam satelit B dikonfigurasikan untuk mengawal paksi oleng, anggul dan rewang dengan menggunakan pengawal terbitan berkadaran. Kedua-dua algoritma kawalan telah disimulasi menggunakan perisian MATLAB®/ SIMULINK®. Algoritma kawalan ini telah diuji dengan menggunakan model mudah medan magnet bumi bagi misi angkasa. Prestasi atitud satelit bagi pilihan ini dibandingkan dan didapati bahawa kedua-dua algoritma boleh memenuhi keperluan misi. Walau bagaimanapun, satelit B memberikan prestasi atitud yang lebih baik . Secara khusus, paksi olengnya berayun antara -2.4° dan 3.2° manakala paksi anggulnya berayun antara -2.4° dan 2.0°. Akhir sekali , paksi rewangnya berayun secara terkawal antara -1.7° dan 0.4° . Kajian ini dapat memberikan gambaran apabila mereka bentuk sistem magnetik kawalan atitud untuk nano-satelit.

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LIST OF ABBREVIATIONS

ACS	-	Attitude Control System
ECI	-	Earth Centered Inertial
LEO	-	Low Earth Orbit
LVLH	-	Local Vertical Local Horizontal
PD	-	Proportional Derivative

NOMENCLATURE

B	-	Geomagnetic field vector [$Tesla$]
M	-	Satellite's magnetic dipole moment vector [Am^2]
m_E	-	Mass of the Earth [kg]
m_S	-	Mass of the satellite [kg]
G	-	Universal constant of gravitation, G = $6.669\times10^{-11}\ m^3kg^{-1}s^{-2}$
r	-	Geocentric distance [m]
μ	-	Earth gravitational constant, μ = $3.986\times10^{14}\ m^3s^{-2}$
i	-	Inclination [deg]
r_e	-	The Earth radius, $r_e = 6378\ km$
R_{Orbit}	-	Orbit radius [m]
ϕ	-	Roll attitude [deg]
θ	-	Pitch attitude [deg]
ψ	-	Yaw attitude [deg]
I_x, I_y, I_z	-	Satellite's moment of inertia [kgm^2]
ω_x, ω_y, ω_z	-	Satellite's body angular velocity[$rads^{-1}$]
$\dot{\omega}_x$, $\dot{\omega}_y$, $\dot{\omega}_z$	-	Satellite's body angular rate [$rads^{-2}$]
T_x, T_y, T_z	-	External torque [Nm]
T_{cx}, T_{cy}, T_{cz}	-	Control torques [Nm]
T_{dx}, T_{dy}, T_{dz}	-	Disturbance torque [Nm]
M_x, M_y, M_z	-	Magnetic dipole moment of the magnetic torquer [Am^2]
ω_o	-	Orbital frequency [$rads^{-1}$]

μ_f	-	Magnetic moment of the Earth, μ_f=7.96×10^{15} $Wb{\cdot}m^{-1}$
c_{pa}	-	Centre of aerodynamic pressure [m]
c_{ps}	-	Location of solar force [m]
c_g	-	Satellite's centre of gravity [m]
D	-	Residual dipole [$A\ m^2$]
F	-	Force [N]
k_{px}, k_{py}, k_{pz}	-	Proportional gains [$Nmrad^{-1}$]
k_{dx}, k_{dy}, k_{dz}	-	Derivative gains [$Nmsrad^{-1}$]

CHAPTER 1

INTRODUCTION

1.1 General Overview

Some satellite subsystems require a stable satellite to carry out its mission. For example radio communications will require less power if the antenna is made to point toward Earth and solar panels can increase power output if properly directed towards the Sun. Specific payloads like a camera require a stable platform on which the satellite has to have 3-axis control namely roll, pitch and yaw. The orientation of the satellite in space is called its attitude. Figure 1.1 shows a satellite with an output of roll, pitch and yaw attitude angles.

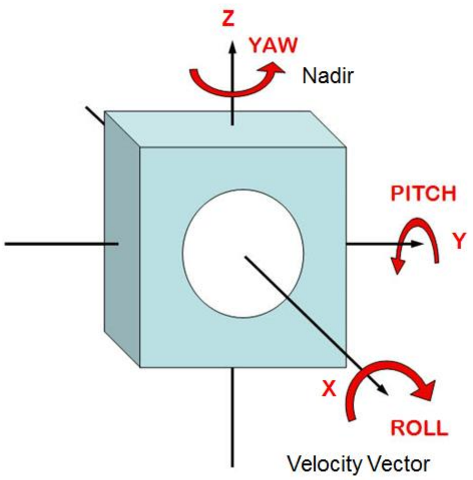

Figure 1.1: Satellite body coordinate system

In space, the satellite has to concern with the presence of natural environmental forces. For small satellites operated in LEO, the dominant disturbance torques are gravity gradient torque, magnetic torque, aerodynamics torque and solar radiation torque. These torques significantly affect the orbital and attitude motions of the satellite by creating undesirable motions, hence counterbalance action is required in the form of attitude control system (ACS). Therefore ACS should have the ability to determine the current attitude, determine the error between the current and desired attitudes and apply torques to remove the error.

This project intends to look into passive and active ACS based on gravity gradient control and magnetic attitude control respectively. Firstly mathematical models of a gravity gradient satellite will be determined. Subsequently this model will be equipped with electromagnetic based device called magnetic torques for active control. Performance of both designs will be tested and simulated in the presence of a simplified geomagnetic field model as well as disturbance torques model using MATLAB/SIMULINK.

1.5 Attitude Control System (ACS)

Attitude Control System (ACS) is an important subsystem in a satellite which functions to stabilize the satellite, orients the satellite in desired directions as well as sensing the orientation of the satellite relative to reference (i.e. inertial) points. Figure 1.2 illustrates a nano-satellite named as M-Cubed designed by University of Michigan's Student Space Systems Fabrication Lab which is configured to align one of its axes with the local Earth magnetic field direction.

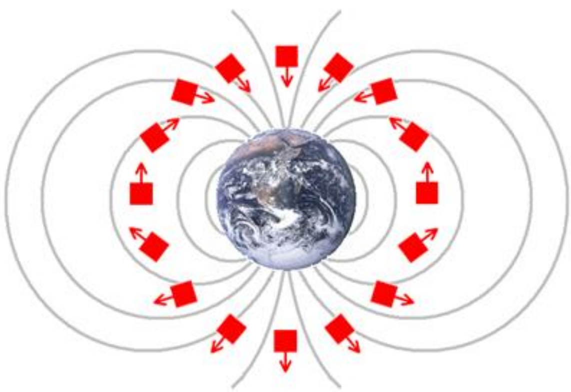

Figure 1.2: A magnetic attitude control system to achieve a proper orientation for Earth-imaging (Web 1, 2013).

Design of ACS varies according to mission of satellites and their attitude requirement. The basic types of control systems are spin, three-axis active and passive or gravity gradient control systems. In general, an ACS consists of four major functional parts: sensor, controller, actuator and satellite dynamics. The sensor determines satellite attitude. The controller programs the electronic signals in a correct sequence to the actuator which is torque producing elements that can rotate the satellite about its center of mass. The resulting motion or dynamics is then monitored by the sensor which closes the loop of ACS as shown in Figure 1.3.

In this work the satellite's orbit is set at LEO that is a distance between 160 kilometers and 2,000 kilometers above the Earth's surface. Its mission is specified to be a nadir pointing mission meaning one of the axes will point toward the Earth. The other two axes will be normal to the orbital plane and towards the satellite's orbital motion respectively. This work will specifically look into a gravity gradient stabilized satellite which is a passive system as well as magnetic attitude system which is an active system.

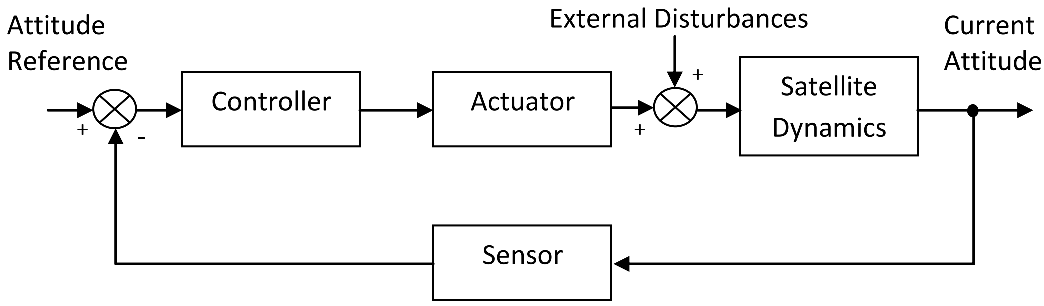

Figure 1.3: General closed loop system for satellite attitude control

1.3 Nano-Satellites

Nano-satellite is applied to an artificial satellite with a mass between 1 and 10kg. Majority of development comes from academia, and normally they follow CubeSat specification. The concept of standard Nano-satellite type, 1-kg 'CubeSat' Nano-satellite had been introduced since 1999 with the main goal to promote a low cost platform for space development and serve as educational tool for university student to design and develop a fully working satellite. The standard 10×10×10 cm basic CubeSat is often called a "1U" CubeSat meaning one unit. CubeSats are scalable along only one axis, by 1U increments. Hence they are CubeSats as "2U" CubeSat (20 × 10 × 10 cm) and "3U" CubeSat (30 × 10 × 10 cm). Figure 1.4 shows four different types of CubeSats.

Constraints on the technical capacity of the people that are involved, cost limitation as well as lack of size mean restraint in complexity of the design, weight and energy resource that a nano-satellite can carry to name a few. Therefore requirements of the systems on board together with payloads that can be carried are preferably low cost, low energy with simple hardware requirement. Accordingly requirement for attitude control is moderate. ACS using gravity gradient and magnetic attitude control methods are some of the techniques that are popular and highly used whether alone or with a combination with other actuators.

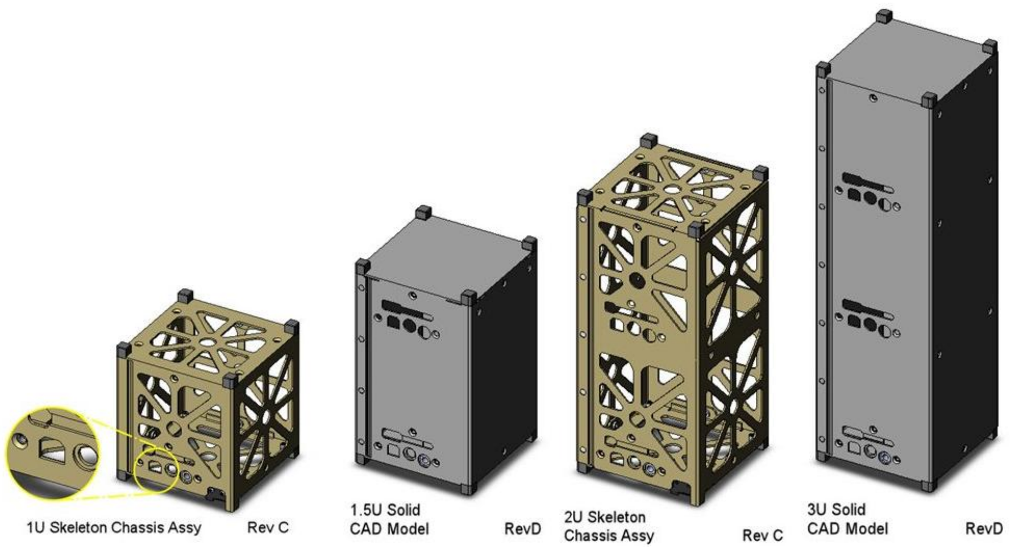

Figure 1.4: CubeSats order from left to right: 1U, 1.5U, 2U, and 3U. (Web 2, 2013)

1.4 Problem Statement

The emergence of nano-satellites has greatly increased the interest in attitude control system research and development among educational institutions. Among these are systems that have combination of actuators such as momentum wheel and magnetorquers together which could improve the angular orientation of the satellite as shown by Candini *et al*. (2012) and Dechao *et al.* (2013). However, high failure rate of nano-satellites when they are in orbit, show precautions are required for usage of a system that require high processing on the CPU (Web 3, 2013). Therefore applying a moderate system that has been applied and proven successful in previously launched micro-satellites could increase the probability of having successful mission. The problem considered in this thesis consists of stabilizing the attitude of a nadir pointing nano-satellite in LEO through usage of a passive gravity gradient stabilization or affiliated with magnetic stabilization using magnetic torques. The techniques need to consider a variety of disturbances that is anticipated in the orbit and exploit them in satellite dynamics model.

1.5 Objectives of Project

The objectives of this project are as follows:

(i) To model a simplified geomagnetic model
(ii) To establish the mathematical models of a gravity gradient satellite equipped with three magnetic torquers
(iii) To control the attitude of the satellite in the presence of the disturbances by using the magnetic torques
(iv) To compare the performance of both the passive and active ACS design which are based on purely gravity gradient and magnetic control respectively

1.6 Scope of Project

The work undertaken in this project is limited to the following aspects:

(i) Only nano-satellites are considered
(ii) Satellite’s mission: Earth pointing small satellite at Low Earth Orbit (LEO)
(iii) A gravity gradient satellite equipped with three magnetic torquers as actuators

(iv) Simulation work using MATLAB/SIMULINK as a platform to evaluate the attitude control algorithms

1.7 Methodology

The research work undertaken in the following five development stages:

(i) Literature review.
(ii) Mathematical model of a simplified geomagnetic field.
(iii) Establish mathematical models of a gravity gradient satellite with three magnetic torques as actuators in active system.
(iv) Consider in orbit external disturbances.
(v) Perform simulation using MATLAB/SIMULINK.
(vi) Comparative study and future work.

1.8 Thesis Outline

The rest of this thesis contains another five chapters. Chapter 2 reviews literatures related to this work. The focus is on the gravity gradient technique and magnitude attitude control technique. Chapter 3 briefly describes theories used in modeling a simplified geomagnetic field, satellite's kinematics and dynamics and external disturbance torques.

Chapter 4 describes the development of the simplified geomagnetic field. It is followed by the modeling for dynamic equations of motion of the defined nano-satellite and external disturbances. Chapter 5 shows results of simulations using MATLAB/SIMULINK which have been obtained. Finally Chapter 6 concludes the work that has been done so far and discusses possible future works.

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